Chapter

Nutrient Solution for Hydroponics

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Abstract

Hydroponics is a profitable, sustainable agricultural method and environmental friendly technology for growing plants without soil. It is the fastest-growing agriculture sector, rapidly gaining momentum and popularity, and could dominate food production in the future. Nutrient solution and its management are the cornerstone of a successful hydroponic system and are the most important determinant of crop production and quality, which is largely dependent on the extent to which plant nutrients are acquired from the nutrient solution. All nutrients in the solution in balanced ratio are supplied directly to the plants and the composition of the solution must reflect the uptake ratio of individual elements by the crop. A balanced supply of nutrients is a prerequisite for the efficient use of resources, and stabilization of the solution pH, electrical conductivity, O_2 level, and temperature is essential for optimum crop yield in hydroponic systems. In this chapter, the composition of the nutrient solution, nutrient availability which is affected by many factors, and the management of the nutrient solution are discussed.

Keywords: nutrient solution, pH, EC, solution temperature, nutrient management

1. Introduction

Hydroponic techniques have been developed to facilitate cultivation under diverse environments and to improve farming practices using soilless methods. In this novel world, hydroponic farming makes efficient use of fertilizers and water, increases productivity, and provides better crop quality; **Table 1** shows the difference in productivity between soil and soilless culture for different crops [1]. Also, due to the risks of soil and water contamination in metropolitan areas, this technique has a potential alternative to agricultural production in cities. Hydroponic systems irrespective of their scale reduce dependence on the soil as a substrate and instead derive nutrition directly from the hydroponic solution comprising of water and nutrients [2]. Because hydroponics provides better control of plant growth, it is possible to achieve high quality and productivity through careful management of—nutrient composition, dissolved O_2 concentration, temperature, pH, and electrical conductivity (EC) of the nutrient solution. Nutrient supply in hydroponics can significantly influence the nutrition, taste, texture, color, and other characteristics of fruit and vegetable crops [3]. In hydroponics, essential nutrient elements are dissolved in appropriate concentrations and relative ratios to achieve the normal growth of plants [4]. It is well known that the productivity and quality of crops grown in hydroponic systems are markedly dependent on the extent of the plant nutrients acquisition

Crop	Hydroponic system production (Kg/ha)	Open-field production (Kg/ha)
Rice	13,456.56	841.03–1009.25
Maize	8971.0	1682.07
Peas	15,699.32	2242.76
Tomato	403,335.81	11,203.75–22,407.47
Potato	156,852.29	17,925.98
Cabbage	20,184.84	14,577.94
Cucumber	31,398.64	7849.66
Lettuce	23,548.98	10.092.42

Source: Singh and Singh [1].

Table 1.
Yield comparisons for different crops between hydroponic and open field cultivation.

from the growing medium [5]. Due to this, nutrient solution and its management are the cornerstone for a successful hydroponics system and are the most important determining factors of crop yield and quality.

2. Plant nutrients

Plant nutrients used in hydroponics are dissolved in water and are mostly in inorganic and ionic forms. All the essential elements for plant growth are supplied using different chemical combinations and establishing a nutrient solution that provides a favorable ratio of ions for plant growth and development is considered an important step in cultivating crops in hydroponic systems [6]. Plant uptake of nutrients can only proceed when they are present in an available form for absorption, and in most situations, nutrients are absorbed in an ionic form. Ions are electrically charged forms of each nutrient, some are cations (positively charged) and others are anions (negatively charged). For example, nitrogen is absorbed as ammonium (NH_4^+, a cation) or nitrate (NO_3^-, an anion); **Table 2** shows the available form of each nutrient and different nutrient solution formulas which have been established by many scientists. There are various standard nutrient solutions, such as the Hoagland and Snyder [13], Hoagland and Arnon [11], Steiner [14] Bollard [15], and others. These standard solutions are good as a general guideline but are not adapted to specific growing conditions. The function of a hydroponics nutrient solution is to supply the plant roots with water, oxygen, and essential mineral elements in soluble form. A nutrient solution usually contains inorganic ions from soluble salts of essential elements required by the plant. However, some organic compounds such as iron chelates may be present [16]. A total of 17 elements are considered essential for most plants, these are carbon, hydrogen, oxygen, nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, iron, copper, zinc, manganese, molybdenum, boron, chlorine, and nickel [17]. An essential element has a clear physiological role, and its absence prevents the complete plant life cycle [18]. Among the minerals, N, P, and K are the most decisive elements in plants [6]. Some other elements such as sodium, silicon, vanadium, can stimulate growth, or can compensate for the toxic effects of other elements, or may replace essential nutrients in a less specific role. Tahereh et al. [19] reported that the plants grown in the absence

Element	Form taken up by plants	Hoagland & Arnon	Hewitt	Cooper	Steiner
		mg L^{-1}			
Nitrogen	NH_4^+, NO_3^-	210	168	200–236	168
Phosphorus	HPO_4^{-2}, $H_2PO_4^-$	31	41	60	31
Potassium	K^+	234	156	300	273
Calcium	Ca^{2+}	160	160	170–185	180
Magnesium	Mg^{2+}	34	36	50	48
sulfur	SO_4^{2-}	64	48	68	336
Iron	Fe^{2+}, Fe^{3+}	2.5	2.8	12	2–4
Copper	Cu^{2+}	0.02	0.064	0.1	0.02
Zinc	Zn^{2+}	0.05	0.065	0.1	0.11
Manganese	Mn^{2+}, Mn^{4+}	0.5	0.54	2	0.62
Boron	H_3BO_3, BO_3^-, $B_4O_7^{2-}$	0.5	0.54	0.3	0.14
Molybdenum	MoO_4^{2-}	0.01	0.04	0.2	Not considered

Source: Salisbury and Ross [7]; Cooper [8]; Steiner [9]; Windsor and Schwarz [10]; Hoagland and Arnon [11]; Hewitt [12].

Table 2.
Nutrient's form taken up by plants and nutrients compositions as suggested by different scientists.

of silica would be weak and show abnormal growth, and proper application of this nutrient can increase consistency and disease resistance, reduce the outbreak of nutrient deficiencies, improve product quality and increase crop yield. In hydroponics, all the nutrients are in a balanced ratio which is directly supplied to the plants, and composition must reflect the uptake ratio of individual elements by the crop, as the demand between species differs, and must be specific for each crop [20]. It is very important to keep ionic balance in the nutrient solution since plant growth and productivity can be negatively affected by the improper relationship between the essential nutrients, that is, the ratio of anions: NO_3^-, $H_2PO_4^-$ and SO_4^{2-}, and the cations K^+, Ca^{2+}, Mg^{2+} [21], and a change in the concentration of one ion must be accompanied by either a corresponding change for an ion of the opposite charge, a complementary change for other ions of the same charge, or both [12]. However, for most common crop plants, critical levels for most nutrients have been determined [22].

2.1 Plant nutrients interaction

Nutrients in the nutrient solution have great interactions that may gain either positive or negative effects on crop production, depending on crop growth stages, amounts, combinations, and balance [23]. Inadequate or excessive concentrations of minerals or an imbalanced ion composition in the nutrient solution may inhibit plant development, resulting in toxicity or nutrient-induced deficiencies [24]. In crop plants, the nutrient interactions are generally measured in terms of growth response and change in concentration of nutrients. Nutrient interactions may be positive or negative and also possible to have no interactions. Interaction between nutrients occurs when the supply of one nutrient affects the absorption and utilization of other nutrients. This type of interaction is most common when one nutrient is in excess concentration in the growth medium. Upon the addition of two nutrients, an increase in crop yield that is more than adding only one, the interaction is positive (synergistic). Similarly, if adding the two nutrients together produced less yield as compared to individual ones, the interactions are negative (antagonistic). When there is no change, there is no interaction. However, most interactions are complex and better understanding of nutrient interactions may be useful in understanding the importance of a balanced supply of nutrients and consequently improvement in plant growth or yields [25]. According to Marschner [26], at the level of the nutrient acquisition mechanisms, competitive or antagonistic phenomena among elements can occur, for example, the interaction between NH_4^+ and K^+, and this could be crucial for NH_4^+ fed plants when exposed to a suboptimal/unbalanced availability of K^+ because the competition could induce/exacerbate K^+ deficiency [27], and it is more relevant when the additional application of NH_4^+ is of pivotal role to achieve specific qualitative objectives of the edible fruits [28]. The interactions between K^+/Na^+ and Cl^-/NO_3^- could represent a limiting factor for soilless cultivation of crop plants, especially in a semiarid environment characterized by saline water. NaCl interferes with the uptake processes of both K^+ and NO_3^-, since K^+ is sensitive to Na^+ in the external environment, while the uptake of NO_3^- is inhibited by Cl^- [29]. This phenomenon could be even more pronounced in hydroponic solutions particularly when used in a closed system, where monitoring the ratio between Ca^{2+}, Mg^{2+}, and K^+ in the solutions is very important to avoid K^+/Ca^{2+} induced Mg^{2+} deficiency. Calcium, magnesium, and potassium compete with each other and the addition of any one of them will reduce the uptake rate of the other two [26]. Unbalanced fertilization practice, with a high level of K^+ and Ca^{2+}, can induce Mg^{2+} deficiency in crop plants, Schimansky [30] suggested that the excessive availability of K^+ and Ca^{2+} could inhibit Mg^{2+} uptake by roots. Similarly, very high rates of Mg^{2+} fertilizers will depress K^+ absorption by plants, but this antagonism is not nearly as strong as the inverse relation of K^+ on Mg^{2+} [31]. Also, the uptake of nitrogen, sulfur, and iron is not exclusively dependent on its availability in the hydroponic solution but also on the presence of other elements. The uptake of NO_3^- was hampered by the shortages of iron and sulfur, and the effect on the assimilation process seems to play a dominant role in determining the NO_3^- accumulation at the leaf level. In the case of nitrogen and sulfur, the lacking one represses the assimilation of the other and induces physiological changes aiming at re-balancing the contents in the plant [32]. One of the greatest issues concerning hydroponic productions is sulfur starvation due to a consistent accumulation of NO_3^- in plant leaves [33]. The anion which is taken up relatively slowly can also reduce the uptake speed of its counter-ion, as observed for SO_4^{2-} on K^+ uptake [26].

In hydroponic solutions, interactions among solutes cannot be neglected and therefore ion activity should be used in calculations instead of concentrations [34]. The high ionic concentrations can disrupt membrane integrity and function, as well as internal solute balance and nutrient absorption, resulting in nutritional deficiency symptoms similar to those observed when nutrient concentrations are below the required levels [24]. In addition, the root physiological process is not only affected by the availability levels of the nutrients, but also by the nutrient sources and/or by the interactions among the different nutrients [35]. The chemical forms of a nutrient are also very important, for example, plants can use a wide variety of nitrogen forms, ranging from the inorganic, namely NH_4^+ and NO_3^-, to the organic ones, like urea and amino acids [36]. Ammonium is an attractive nitrogen form for root uptake due to its permanent availability and the reduced state of the nitrogen; nevertheless, when both nitrogen forms are supplied to the nutrient solution, plant roots may absorb preferentially one of them, depending on the heredity of each specie [37]. Pure NH_4^+ nutrition caused the development of toxicity symptoms in many herbaceous plants, as well as inhibited NO_3^- uptake [38]. Therefore, a balanced nitrogen diet is clearly beneficial for several plant species as compared to that based exclusively on NO_3^- [39]. Tomato root growth was optimal when NO_3^- and NH_4^+ were supplied in a 3:1 ratio; on the contrary, when NH_4^+ concentration was too high, a strong inhibition in the root development was observed [40]. However, the form of nitrogen suitable for obtaining the maximum production for each species and its cultivation conditions has not yet been defined [37]. Also, the plant species and environmental conditions are two critical factors that affect the optimum NO_3^-/NH_4^+ ratio, which can affect not only root development and morphology but also the overall root biomass. According to [41], the chemical quality of nutrient solutions can affect plant yield and bioactive compounds.

Several physical-chemical phenomena can alter the nutrient availability for plants, the most important of which are—precipitation, co-precipitation, and complexation. Precipitation reactions may occur when cations and anions in an aqueous solution combine to form a precipitate. It is known that phosphate availability can be reduced at pH above 7 mostly due to precipitation with calcium and different calcium-phosphate minerals can potentially form above this pH [42], and precipitation of phosphates must be avoided in hydroponic solutions because it is not only depleting phosphorus from the nutrient solution, but it may also reduce the solubility of other nutrients, such as calcium, magnesium, iron, and manganese. Also, sulfur availability can be limited by precipitation with calcium, as calcium-sulfate minerals [43]. Co-precipitation also may strongly reduce the solubility of nutrients added at trace concentrations, such as copper, zinc, manganese, and nickel, when insoluble compounds, such as iron hydroxides, calcium carbonates, or calcium phosphates, are formed [44]. In hydroponic solutions, a complex chemical compound is formed when a metal nutrient is bound by one or more neutral molecules or anions, either of organic or inorganic nature. The resulting complex can be a neutral compound, a cation, or an anion, depending on whether positive or negative charges prevail. These reactions diminish the concentration of the free ions in the nutrient solution, changing elemental bioavailability. The addition, organic ligands, such as: ethylenediaminetetraacetic acid (EDTA), Diethylenetriamine Penta acetic Acid (DTPA), Ethylenediamine (O-Hydroxyphenyl acetic) Acid (EDDHA), and citrate, can increase the stability of certain elements in solution, especially iron, copper, and zinc [45].

3. PH level of the nutrient solution

The pH value of the nutrient solution greatly affects plants' growth. This is because the nutrients added to the nutrient solution are available for the uptake by the plant are soluble in water only at particular pH levels, as shown in **Figure 1**. According to Mayavan et al. [47], the plants require a range of pH values to be maintained to ensure the availability of all the nutrients for uptake by the plants. Nutrient solution pH is typically managed between 5.5 and 6.5, and it seems to be a range where almost all hydroponically grown crops exhibit normal growth and nutrient uptake, and the optimum pH range for different crops grown hydroponically are shown in **Table 3**. However, species-specific pH responses of leafy greens grown in liquid culture hydroponic systems are largely unexplored [49]. However, the optimum pH for maximum growth differs not only between species, but also between cultivar,

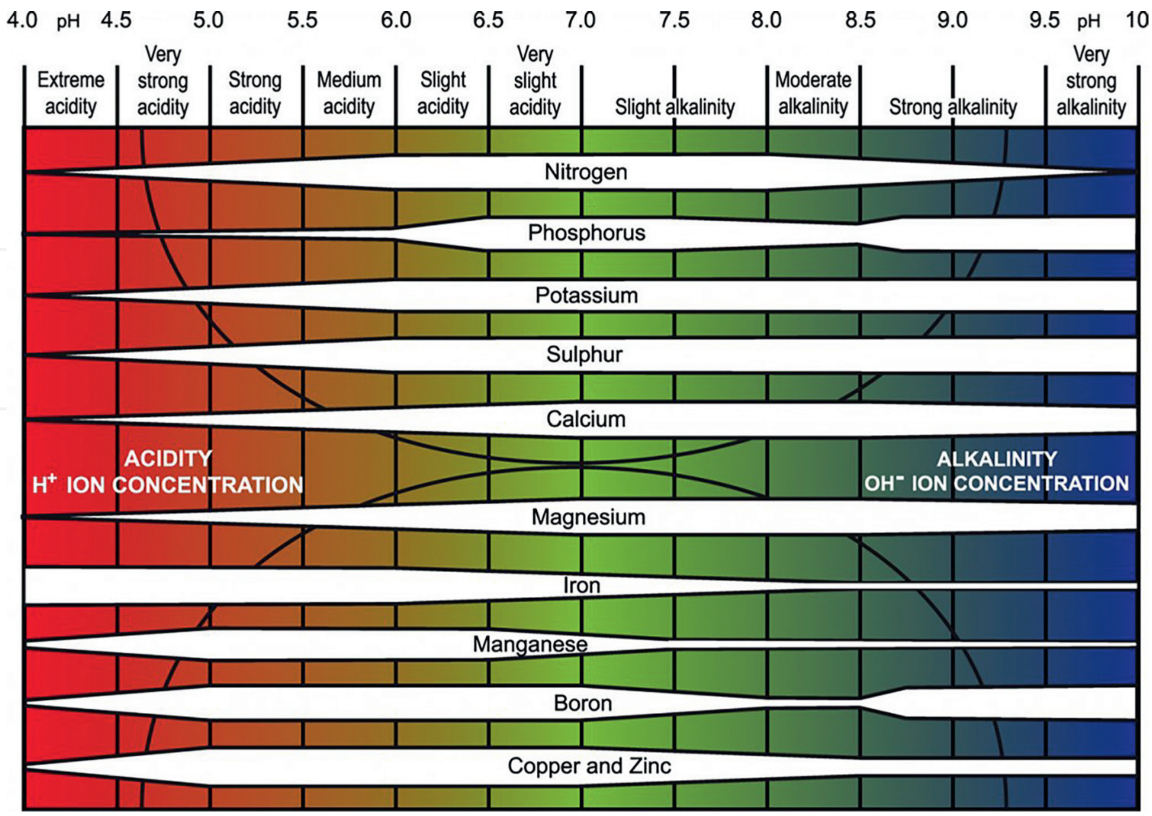

Figure 1.
The availability of different nutrients at the different pH bands is indicated by the width of the white bar: The wider the bar, the more available is the nutrient. Source: Truog [46].

Crop	Optimum pH range
Tomato	6.0–6.5
Pepper	5.5–6.0
Egg plant	6.0
Cucumber	5.0–5.5
Strawberry	6.0
Courgettes	6.0
Banana	5.5–6.5
Ficus	5.5–6.0
Spinach	6.0–7.0
Lettuce	6.0–7.0
Cabbage	6.5–7.0
Broccoli	6.0–6.8
Asparagus	6.0–8.0
Bean	6.0
Basil	5.5–6.0
Sage	5.5–6.5

Source: Sharma et al. [48].

Table 3.
The optimum range of pH values for different crops grown hydroponically.

climatic conditions, and soil, substrate, or nutrient solution conditions [50]. Frick and Mitchell [51] indicated that the pH of a hydroponic nutrient solution fluctuates because of the unbalanced anion and cation exchange reaction with roots and there is no buffering capacity in hydroponics. The changes in the pH of a nutrient solution depend on the difference in the magnitude of nutrient uptake by plants, in terms of the balance of anions over cations. When the anions are up taken in higher concentrations than cations, for example, nitrate, the plant excretes OH^- or HCO_3^- anions, to balance the electrical charges inside, which produces increasing in the pH value and this process is called physiological alkalinity [52]. Nutrient disorders and thereby growth reduction occur when pH is outside the optimum range, and several studies suggested that the direct effect of pH seems to be detrimental only at the extreme ends of acidity and alkalinity, and growth reductions and nutrient disorders outside of the conventional pH ranges can typically be attributed to pH-dependent factors [49, 53]. The growth response to pH is species-specific and further studies to investigate responses to pH of commercially important cultivars and species grown hydroponically need to be done [49]. In general, the pH of the plant root environment is affecting nutrient uptake, nutrient availability, ion antagonism, ionic species present, and solubility of fertilizer salts [50, 54]. Due to this, it is important to measure and maintain the pH value to the required level because a little drift in the pH value can make a lot of nutrients unavailable for the plants [47].

Precipitation/dissolution phenomena are often promoted by pH changes and, therefore, pH must be continuously controlled or buffered. Cations may form insoluble hydroxides at alkaline pH or other insoluble precipitates by reacting with other anionic nutrients. PH values above 7 may cause the precipitation of iron, zinc, copper, nickel, and manganese as insoluble hydroxides [55]. Also, at high pH values and high dissolved CO_2 concentrations, macronutrients like calcium and magnesium can precipitate as carbonates. As the pH increases above 7, most of the dissolved phosphorus reacts with calcium forming calcium phosphates. Gradually, reactions occur in which the dissolved free phosphate species form insoluble compounds that cause phosphate to become unavailable [56]. According to Resh [57], slightly acidic pH is optimum for hydroponic production because iron, manganese, calcium, and magnesium may form precipitates and become unavailable at pH above 7. Bugbee [58] also reported that availability of potassium and phosphorus is slightly reduced in a nutrient solution with high pH. The reason for the reduction in phosphorus uptake at a high pH level is explained by the reduction in the concentration of $H_2PO_4^-$, which is the substrate of the proton-coupled phosphate symporter in the plasma membrane, in the pH range of 5.6–8.5; conversely, a decrease in pH can increase the activity of proton-coupled solute transporters and enhance anion uptake [59]. Because pH affects nutrient availability and nutrient uptake across the plasma membrane, it is difficult to determine whether growth inhibition and nutrient disorders observed at low pH of the nutrient solution are a result of the direct effect of excessive hydronium ion concentration or pH-dependent factors affecting nutrient availability and uptake. At acidic pH, for example, in uncontrolled hydroponic systems under anoxic conditions, some elements might also precipitate as insoluble sulfides. Also, it is very important to note that, the addition of nutrients in the form of salts to hydroponic solutions may lead to hydrolysis reactions, which may result in the acidification or alkalinization of the medium. For example, nitrogen supply may alter solution pH, if nitrogen is added only in the form of NO_3^- (alkalinization) or NH_4^+ (acidification) [60].

In general, stabilizing the pH of a nutrient solution is necessary for optimum crop productivity in hydroponics [51], and maintaining an adequate nutrient solution and pH level are often cited as major obstacles to hydroponic production [61]. Despite the fact that the optimal pH in the root zone of most crops grown hydroponically ranges from 5.5 to 6.5, although values as low as 4.0 have been proposed for preventing the incidence of infections from Pythium and Phytophthora spp. [13, 49]. Low pH in the rhizosphere poses abiotic stress, resulting directly (i.e., high H^+ injury of roots) or/and indirectly (i.e., limited availability of phosphorus) in restricted plant growth and crop yield. The value of pH changes as the plant absorbs nutrients from the solution, the plants give hydrogen ions into the nutrients in exchange for the ions of elements they require, and they do this to be electrically neutral. The hydrogen ions that the plants get are a result of photosynthesis. These hydrogen ions combine with water to produce hydronium ions which increases the pH of the water. This has to be counteracted by adding acids like phosphoric acid into the nutrient solution to ensure the solubility of all the elements in the nutrients [47]. Various acids or bases used to adjust pH may also provide some interacting factors on the plants. For example, potassium hydroxide, sodium hydroxide, phosphoric acid, and acetic acid are commonly used to maintain the pH of the nutrient solution. The presence of these acids or bases may have had small impacts through the addition of minerals such as potassium, phosphorus, and/or sodium and the increased concentration of acetates. Other nonmineral nutrients containing acids (carbonic, formic, citric, acetylsalicylic, etc.) could be used for pH adjustment, but their potential toxicity and interactions with the nutrient solutions would need careful consideration and study. Overall, it would be ideal to have a solution where pH could be maintained easily within a small pH range without the addition of mineral nutrients [62]. Wang et al. [63] found that a mixture of three (HNO_3, H_3PO_4, and H_2SO_4) acids was much more effective than only single acid for maintaining an optimal solution pH of 5.5–6.5. The management of nutrient solution pH is an important challenge in soilless systems, since not only it may determine plant growth but also it influences dry matter production, root rhizosphere, and apoplastic pH [13]. However, in soilless culture, when maintaining marginal values of the optimum pH range, the risk of exceeding or dropping below them for some time increases due to the limited volume of nutrient solution per plant that is available in the root zone, and most plants, when exposed to external pH levels >7 or < 5, show growth restrictions. When soilless substrates are used instead of liquid-based hydroponics, pH in the nutrient solution interacts with substrates [64], and micronutrient toxicity occurs rather than deficiency. Therefore, the evaluation of the plant's pH response must consider the growing systems employed.

4. Nutrient solution electrical conductivity

In soilless culture, the total salt concentration of a nutrient solution must be considered, and the nutrient solution EC is an index of salt concentration and an indicator of electrolyte concentration of the solution and is related to the number of ions available to plants in the root zone. The EC is a measure of the total salts dissolved in the hydroponic nutrient solution. It is used for monitoring applications of fertilizers. However, EC reading does not provide information regarding the exact mineral content of the nutrient solution. It is an important factor that reflects the total content of macro- and micro-elements available to plants [6], and it is an easy and accurate method of measuring total salt concentration. Inadequate management of the nutrient solution, such as the use of a too high or a too low concentration of the nutrient solution, or an imbalanced ion composition could inhibit plant growth due to either toxicity or nutrient-induced deficiency [65]. In hydroponic production systems, EC management is one of the most important and manageable cultural practices that affects the visual, nutritional, and phytochemical quality of leafy vegetables [4]. However, managing the EC in moderately high levels—either by using low-quality water that contains residual ions, such as Cl^-, Na^+ and SO_4^-, or by adding major nutrients through stock solutions—is a cultivation management technique that provides great potential to achieve high dietary and organoleptic quality in fresh vegetables [24]. Each plant species has a proper uptake rate of the nutrient solution; excessively high or low levels of the nutrient solution have a negative effect on plants. For many leafy vegetables, there are already specific formulations used on a commercial scale for hydroponics, and the optimum EC levels for different crops grown hydroponically are shown in **Table 4**. Although the plants were supplied with suitable ion ratios, plants can easily suffer from nutrient deficiency or excess if the nutrient solution concentration is low or high. Therefore, it is crucial to determine the suitable EC level of nutrient solutions with favorable ion ratios for growing plants [6]. The optimal EC is crop specific and depends on environmental conditions [66]. Thus, the determination of the most favorable nutrient ratio for each species under diverse climatic conditions is of major importance.

Many studies have reported that EC levels of nutrient solutions affect the growth of various crops. The optimal EC level range should be from 1.5 to 3.5 dS m^{-1} for most hydroponic crops, but this value varies between crop species and phenological stages [6]. However, the upper levels of EC in nutrient solutions must be considered for each species, since excessive EC values may decrease the osmotic potential of the nutrient solution and consequently result in delays in water transport from roots to fruits, with negative effects on fruit expansion and yield [24]. The EC levels showed a considerable

Crop	**EC (dSm^{-1})**
Tomato	2.0–4.0
Pepper	0.8–1.8
Egg plant	2.5–3.5
Cucumber	1.7–2.0
Strawberry	1.8–2.2
Courgettes	1.8–2.4
Banana	1.8–2.2
Ficus	1.6–2.4
Spinach	1.8–2.3
Lettuce	1.2–1.8
Cabbage	2.5–3.0
Broccoli	2.8–3.5
Asparagus	1.4–1.8
Bean	2.0–4.0
Basil	1.0–1.6
Sage	1.0–1.6

Source: Sharma et al. [48].

Table 4.
Optimum range of EC values for different crops grown hydroponically.

influence on the ratio of ions as well as the uptake content of individual minerals. Too low and too high EC would reduce yields, visual quality, phytochemical compounds and lead to a less attractive color and taste to consumers, and enhance the negative health effects due to nitrate accumulation [4]. Increasing conductivity in nutrient solution may reduce water absorption by plants and decrease photosynthesis [67]. Also, higher EC means plants are exposed to salinity stress and high levels of nutrients, which hinders nutrient uptake and induces osmotic stress, ion toxicity, nutrient imbalance, wastes nutrients, and increases the discharge of more nutrients into the environment, resulting in environmental pollution. At the extreme EC level, plants are not able to take up any more water, and water will move backward out of the nutrient solution, which makes plants withered. The elevated EC may have negative effects on yield but can also positively affect the quality of the fresh produce, thus compromising any yield losses through the production of products with a high added value [24]. As an example, the yield of tomatoes under the hydroponic system increased as EC of the nutrient solution increased from 0 to 3 dS m^{-1} and decreased as the EC increased from 3 to 5 dS m^{-1} due to an increase in water stress [68]. Lower EC values mean the supply of some nutrients to the crop may be inadequate are mostly accompanied by nutrient deficiencies and decreasing yield [69]. So, appropriate management of EC in hydroponics technique can give an effective tool for improving vegetable yield and quality [48].

EC is modified by plants as they absorb nutrients and water from the nutrient solution. When a nutrient solution is applied continuously, plants can uptake ions at very low concentrations, and a high proportion of the nutrients are not used by plants. However, in particular situations, too low concentrations do not cover the minimum demand for certain nutrients. On the other hand, high concentrated nutrient solutions lead to excessive nutrient uptake and therefore toxic effects may be expected. Therefore, a decrease in the concentration of some ions and an increase in the concentration of others is observed simultaneously, both in close and open systems. It was observed, in a closed hydroponic system with a rose crop, that the concentration of iron decreased very fast, while that of Ca^{2+}, Mg^{2+}, and Cl^- increased; moreover, concentrations of K^+, Ca^{2+}, and SO_4^{2-} did not reach critical levels [70]. Providing the most suitable nutrient solution and EC level for growing vegetables and crops in hydroponic systems helps to avoid the waste of nutrient solution, which contributes to saving production costs for growing crops in plant factories and preventing environmental pollution, and the value of EC is required to be controlled to ensure nutritional elements needed by plants is fulfilled.

5. Nutrient solution temperature

Nutrient solution temperature is considered as one of the most important determining factors of crop yield and quality in hydroponic production systems [71]. The temperature of the nutrient solution affects the physiological process in the root, such as the absorption of water and nutrients, and the thermal regulation of hydroponic solution can contribute to improving and optimizing plant physiological processes [72]. Nutrient uptake for plants grown in glasshouses may be positively and adversely affected by manipulating the hydroponic solution temperature to the optimum level [73]. It is also possible that the increased temperature facilitated solubility of minerals and increase uptake since the rate of dissolving of solutes increases with increase in temperature [74], and the nutrient solution temperature tends to determine the concentration of nutrients absorbed by the plant, as more nutrients are dissolved at higher temperatures and less at lower temperatures, consequently influencing the efficiency of the photosynthetic apparatus [75]. Calatayud et al. [76] revealed that, in most plant species, nutrient uptake by roots decreased at low temperatures. Increasing nutrient temperatures increased nutrient uptake in cucumber and enhanced plant growth leading to a significant increase in yield [77]. The uptake rate of N, P, K, Na, Fe, Mn, and Zn in Jojoba was significantly reduced at low temperatures [78]. While, in cucumber, uptake of N, P, K, Ca, and Mg was increased when the temperature was raised in a closed hydroponic system from 12 to 20°C [77]. It has been reported that commercial growers experience a lower level of ornamental plant production in winter than in summer due to the low temperature of the solution [79, 80]. Also, the production of various plant metabolites is influenced by the temperature of the root zone in many plants, including leafy vegetables [67].

The chemical equilibrium of the solution is affected by nutrient temperature, and this is particularly crucial for areas where the over warming of the nutrient solution often occurs, impacting also all the physiological processes in the plant [81]. Generally, the cold solution increased NO_3^- uptake and thin-white roots production but decreased water uptake and it also influenced the photosynthetic apparatus. The temperature of the nutrient solution also has a direct relation to the amount of oxygen consumed by plants, and an inverse relation to the oxygen dissolved. It is of paramount importance to regulate hydroponic solution temperatures in situations whereby, plants are grown in a controlled environment during winter months. Optimizing solution temperature can be achieved by warming the nutrient solution and this showed success in a variety of crops [82, 83]. High temperature in the root zone is one of the most significant limiting factors for lettuce cultivation in tropical hydroponics. Instead of cooling the entire greenhouse air, the root zone cooling system could be an energy-efficient cooling system for a greenhouse for tropical hydroponics. Therefore, it is very important to study the optimum nutrient temperature requirements for different crops grown in climates with adverse winter conditions.

6. Dissolved oxygen levels in nutrient solution

Maintaining enough dissolved O_2 in a nutrient solution in a hydroponic system is crucial for plant health. Oxygen availability to roots grown in soilless culture can become limiting in case O_2 demand exceeds O_2 supply, inducing a reduction in root growth rate, ion, and water uptake, eventually reducing plant production [84]. Plants grown in hydroponic systems can quickly deplete the dissolved O_2 in the nutrient solution resulting in poor root aeration, especially when greenhouse temperatures are high, **Table 5** shows O_2 solubility in pure water at different temperatures. Jong et al. [86] noticed that cucumber growth was significantly affected by root-zone aeration. Roosta et al. [87] found improve eggplant growth with rising O_2 levels in the nutrient solution in floating hydroponic cultures and higher O_2 levels seemed to alleviate signs of ammonium toxicity among the tested plants. Root respiration also decreases when O_2 supply in the root environment falls below a critical O_2 concentration [88]. The sensitivity of roots to low O_2 concentration depends on its effect on mitochondrial respiration because it supplies most of the energy required for root function. Reduction in O_2 levels in the nutrient solution could lead to poor roots, an increase in the incidence of diseases and pests, and a reduction in plant growth. Oxygen around a plant's roots affects the beneficial microorganisms that provide protection from pathogens and improve nutrient uptake. Tomato plant roots would be

Temperature (°C)	Oxygen solubility (mg L^{-1})
10	11.29
15	10.08
20	9.09
25	8.26
30	7.56
35	6.95
40	6.41
45	5.93

Source: Trejo-Téllez et al. [85].

Table 5.
Solubility of oxygen in pure water at various temperatures.

much more susceptible to Pythium infection if root zone O_2 dropped below 2.8 mg/L [89]. Dissolved O_2 concentration, is strongly dependent on solution temperature and flow rate near the root zone, as well as on the growth rate of the crop, and may be influenced by the bacterial community present in the solution. The temperature has a direct relationship to the amount of oxygen consumed by the plant and a reverse relationship with dissolved oxygen from the nutrient solution. The consumption of O_2 increases when the temperature of the nutrient solution increases. Consequently, it produces an increase in the relative concentration of CO_2 in the root environment if the root aeration is not adequate [90]. For overcoming the limited oxygen exchange between the atmosphere and the nutrient solution in static deep water culture hydroponics, the nutrient solution is aerated by an air bubbler connecting with the pump to provide adequate root oxygenation [6]. Roots of loose-leaf lettuce grown in a floating raft hydroponic system were found to have a better condition with oxygen enrichment done in nutrient solution up to aeration pressure of 0.012 mPa and concentration of 600 ppm, with indicators of increasing length and total root surface area [68]. So, it is important to make sure the nutrient solution is properly aerated to maintain enough oxygen for the plant cells found in the root mass since this is crucial to the function of the plant's cells and the microbial world.

7. Nutrient solution management

An optimized and well-balanced supply of nutrients is a prerequisite for efficient use of the resources by hydroponically grown vegetables, not only to ensure a high yield but also to guarantee the quality of the edible tissues. In hydroponics, because of the limited nutrient-buffering capacity of the system and the ability to make rapid changes, careful monitoring of the system is necessary. The frequency and volume of the nutrient solution applied depends on the type of substrate, the crop and growth stage, the size of the container, the irrigation systems used, and the prevailing climatic conditions. Depending on the stage of plant development, some elements in the nutrient solution will be depleted more quickly than others and as water evaporates from the nutrient solution, the fertilizer becomes more concentrated and can burn plant roots. In hydroponics, nutrient management is very important and must be done as highly efficient as possible to improve productivity without harming the environment.

Nutrient management included- application the right fertilizers source (e.g., ammonium or nitrate as nitrogen source), balanced nutrient solution according to plants needs and according to plant growth stages and climatic conditions. The main principle of crop nutrient management is to prevent overapplication of nutrients, which prevents loss due to low yield from toxicities of some nutrients resulting from the unnecessary use of fertilizers. It was reported that the strong difference between the ion ratios presented in the nutrient solution and those absorbed by plants led to the accumulation of certain ions in the nutrient solution, which caused an imbalance of mineral elements in the nutrient solution and created more energy to absorb the suitable ions [6]. Recycling exhausted solutions may also represent an efficient strategy to prevent groundwater and environmental pollution. However, the main problem with the reuse of exhausted nutrient solutions is the shortage of some key macro and micronutrients [91] and their increased salinity [92] causing, in turn, problems for crops [93, 94]. Thus, it is very important to develop management practices/tools that reduce salinity in recycled solutions and/or minimize the physiological impact of salinity on plants. The salinity increase could be contrasted by treating the recycled water with appropriate osmotic systems, including forward and reverse osmosis.

In closed hydroponic systems, accumulation of potentially toxic organic compounds released by the roots of cultivated plants may occur and to overcome this issue, several treatment techniques have been proposed for root exudates degradation or removal. However, for the treatment to be effective, it should be able to remove root exudates without interfering with the inorganic mineral nutrients in the solution. As above-mentioned, the regulation of the solution flow rate in hydroponic production affects plant growth, which in turn affects crop yield and quality. The influence of nutrient solution flow rate on plant growth is related to the plants' physical environment. The flow of nutrient solution not only promotes nutrient ion diffusion but also increases the kinetic energy available to plant roots Therefore, adjusting the flow rate can improve plant yield and a reasonable flow pattern must be carefully selected. Because increasing the flow means increasing electricity consumption, it increases the cost of operation. Therefore, it is important to balance plant yield, nutrient management, and energy utilization. According to Baiyin et al. [95], determining the ideal flow rate for hydroponic production may help to increase yield. However, such a determination requires a specific analysis of each crop and growing environment. The hydroponic nutrient solution is the sole source of nutrients to the plant; therefore, it is imperative that a balanced solution, containing all the right plant nutrients, is applied.

8. Conclusion

Hydroponic cultivation is revolutionizing agricultural crop production techniques all over the world owing to its minimal environmental footprint, enhanced pest control, and provide high crop yield. It allows more accurate control of environmental conditions that offer possibilities for increasing production and improving the quality of crops. The rapid development of computers and controllers has enabled the opportunity to apply the controller in hydroponics. The microcontroller could be used to control these nutrient solution parameters by using relevant sensors. It monitors the conductivity and pH throughout 24 h during the whole cycle of production. Also, it helps in monitoring temperature, nutrient atomization, EC, and pH fluctuations and level of nutrient solution in the nutrient reservoir. However, although the comprehension of the multi-level interactions among the various mineral elements is considered crucial to understanding the different sensing and signaling pathways induced by a single or multiple shortage/s, the impact of these nutrients' interactions on crop performance is largely unknown [32].

Some hydroponic growers use more than the required amounts of nutrients for crop growth to minimize the chances of nutrient deficiency. But one of the most important factors for a successful hydroponics system is the use of the appropriate nutrient solution, and it is important to control the amount of nutrients to allow or deny plants the nutrient accumulation. While hydroponic systems are considered to represent a sustainable method for growing plants, the nutrient solution used in hydroponic systems is based on chemical fertilizers which are mined from scarce and non-renewable resources. Recently, there has been an increased interest in organic hydroponics, as the market for organic food continues to grow and some studies have reported the possibility of growing vegetables using an organic nutrient solution. For optimizing the utilization of organic waste for hydroponic plant growth, a solubilization step is required to break down organic matter and mobilize nutrients [96]. For example, the direct use of organic fertilizers in hydroponic systems may inhibit plant growth due to the high biological oxygen demand in the root zone caused by the presence of dissolved organic carbon compounds. Additionally, most of the nutrients in organic sources, such as waste material from the agricultural and aquacultural industry, are not in ionic forms and, hence, are not directly available for plants. Also, the last decade has seen increasing interest in using wastewater as a source of hydroponic nutrition. This aims at a dual benefit of optimizing water reuse as well as a practical end point for wastewater management. Untreated domestic rinse water obtained from washing machine second-cycle rinse can effectively be used for indoor hydroponic cultivation of plants without the need for any additional fertilizer. It also entails the benefits of significant savings in water use, sewage disposal, ecosystem protection, and the possibility to produce economically viable food crops [97]. Nowadays, hydroponic farming technology is extensively used in producing ornamental plants and flowers. Controllable application of fertilizers, the ability to change nutrients in different weather conditions and different plant growth stages, reduction of fertilizer leaching from the root zone, reduction of contamination, environmental protection, and enhancement of the quality and quantity of products are becoming some of the advantages of this technology.

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